

## Retrospective Registration for Improved Localization of Cortical Stimulation on MR Images.

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**Background:** The gold standard in functional mapping for brain tumor surgery is direct electrical stimulation of the cortex (CS). The advent of functional neuroimaging presents several promising alternatives, including functional MRI (fMRI), magnetoencephalography, and positron emission tomography. To validate these image-based alternatives to CS, studies typically either photograph the cortical surface with tags marking CS locations [1], or make use of neurosurgical image guidance systems [2] to digitize the locations of cortical stimulation measurements. While image guidance systems provide the convenience of recording CS data directly into MR image space, their use is prone to systematic error introduced by brain shift that occurs when the cortical surface is exposed.

Several attempts to correct for brain shift have been made, including intra-operative ultrasound [3] and/or MRI [4]. These approaches have the distinct advantage of providing non-linear transformations to correct for brain shift. However, these solutions require imaging to be performed in the operating room, at the cost of additional time and equipment. A simple alternative approach is to use the image guidance system itself to create a digitization of the cortical surface after brain shift, and use these digitized points to calculate a transformation to correct for brain shift retrospectively.

In this work, we present a first order correction scheme for brain shift, treating the digitized cortical surface measurements as a rigid body. The transformation that minimizes the average distance between the digitized CS points and the brain surface on the image guidance MRI is calculated, using an iterative closest point (ICP) approach. This method is validated in a series of brain tumor patients who received surgical treatment and cortical stimulation as part of their standard care. These patients were positioned on their left or right side during surgery, so we hypothesize that the greatest correction will be needed in the left-right direction, parallel to the gravitational axis.

**Methods:** Cortical stimulation procedures were observed in a series of nine brain tumor patients receiving surgical treatment. During cortical stimulation, a neuronavigation (Medtronic TREON) system was used to record the locations of cortical stimulation onto the image guidance MRI. Brain masks were drawn manually from the image guidance MRI using fslview. AFNI's 3dcalc was used to create a mask of the voxels on the edge of the brain mask (figure 1). Distances inside or outside of the brain surface are calculated using the CS points and the MRI edge-mask.

For the ICP algorithm, the distance from each CS point to the nearest voxel in the edge-mask is determined, and used as the initial cost function. The CS points are then translated by +/- 1 mm, or rotated by +/- 1 degree on each of the x, y, and z axes. The distance between each CS point and the nearest edge-mask voxel, and the associated cost function, is calculated for each transformation. The transformation with the lowest cost function is chosen, and the process is repeated. In this manner the ICP algorithm attempts to globally optimize the transformation, following a steepest-descent path. The ICP algorithm iterates until no transformation improves the cost function.

The cost function used by the ICP algorithm includes a term to minimize the CS-to-MRI surface distance ( $C_D$ ), as well as a term to minimize the distance the CS points are moved ( $C_R$ ), such that  $C = C_D + C_R$ .  $C_D$  and  $C_R$  are calculated as:

$$C_D = \frac{1}{n} \left( \sum D_i^2 \right), \quad C_R = \frac{c}{n} \left( \sum R_i^2 \right)$$

where  $D_i$  is the distance of the  $i$ 'th CS point to a voxel in the edge-mask, and  $n$  is the number of CS points.  $R_i$  is the distance the  $i$ 'th CS point has moved from its starting location, and  $c$  is a weighting factor that can be used to increase or decrease the severity of the cost of moving the CS data-points from their starting locations. In this work  $c=0.5$ , to strike a balance between minimizing the distance between the digitized cortical surfaces and limiting the distance moved from the starting locations.

**Results:** The average distance from the cortical stimulation points to the brain surface before correcting for brain shift was  $3.8 \pm 0.5$  mm. After correcting for brain shift using linear transformations and the ICP algorithm described above, the average distance was reduced to  $1.6 \pm 0.3$  mm. The ICP registration procedure translated the CS points an average of  $4.2 \pm 0.6$  mm on the LR axis,  $1.4 \pm 0.4$  mm on the AP axis, and  $2.1 \pm 0.7$  mm on the SI axis. The CS points were translated by a total distance of  $5.2 \pm 0.8$  mm on average.

**Discussion & Conclusion:** The ICP algorithm successfully reduced the distance between the cortical surface (measured from the MRI), and the digitized CS points (measured by the neuronavigation unit) by nearly 60 percent, using only rigid, linear transformations of the post-brain-shift digitization. We expected that linear transformations would substantially reduce the distance between the pre- and post- brain-shift surfaces, as the major component of brain shift should be along the gravitational axis, and normal to the brain surface. The algorithm performed as expected, correcting more than twice as much shift on the x-axis as the y- or z-axes. Thus, rigid body transformations provide a reasonable first-order correction for brain shift. However, non-linear transformations will likely provide more accurate corrections, at the cost of time and/or added equipment. Digitizing more points from the cortical surface using the neuronavigation unit could potentially be used to calculate non-linear deformations, and more fully correct for brain shift.

**References:** [1] Roux FE, et al., 2000. J. Neurol Neurosurg Psychiatry, 69, 453-63. [2] Bizzzi A, et al., 2008. Radiology, 248(2), 579-89. [3] Bucholz R et al, 1997. Lect Notes Comput Sc, 1205, 459-66. [4] Wittek A, et al, 2005. Lect Notes Comput Sc, 3750, 583-90.

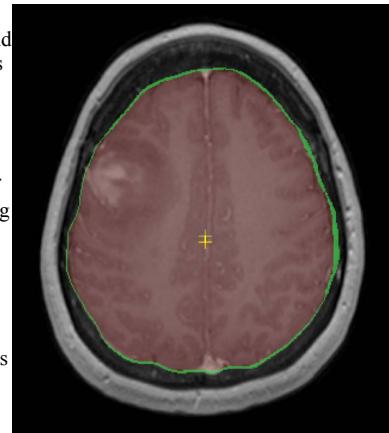


Figure 1: Example brain mask (red) and edge-mask (green). The edge-mask is supplied to the ICP minimization routine along with the cortical stimulation points.

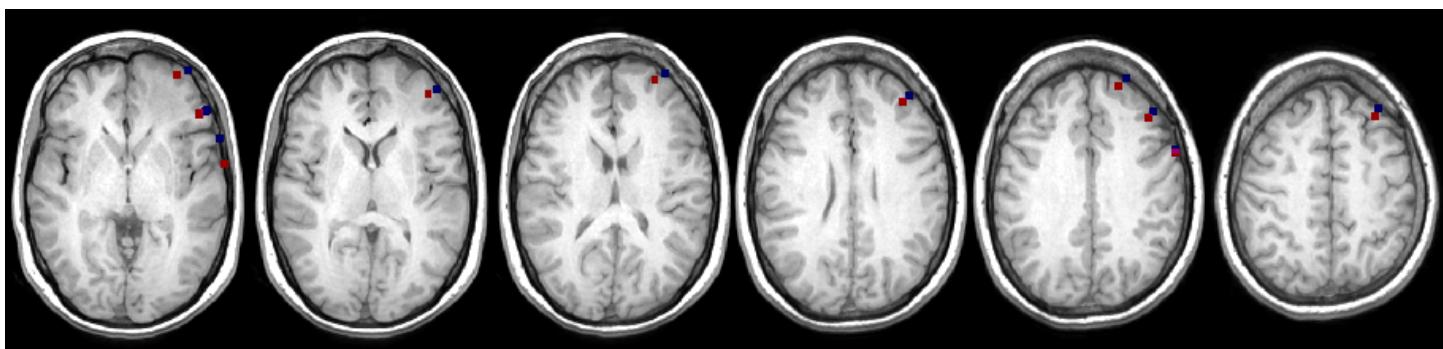


Figure 2: Uncorrected (red) and corrected (blue) cortical stimulation positions. The uncorrected points are mis-registered because of brain shift. After registration using rigid transformations and ICP minimization, the mean distance to the cortical surface for this subject is reduced from 4.4 to 1.0 mm.